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Fracture Studies on High Hardness
BISALLOY 500® Steel

M.Z. Shah Khan, S.J. Alkemade and
G.M. Weston

DSTO-RR-0130

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Fracture Studies on High Hardness BISALLOY 500® Steel

M.Z. Shah Khan, S.J. Alkemade and G.M. Weston

**Maritime Platforms Division
Aeronautical and Maritime Research Laboratory**

DSTO-RR-0130

ABSTRACT

Mechanical properties of a high hardness alloy steel containing microstructural banding were determined in both transverse (T-L) and longitudinal (L-T) orientations with respect to the rolling direction. Tests undertaken included tensile, Charpy impact, fracture toughness, stress corrosion and constant amplitude fatigue. The specimen orientation was found to have little influence on the tensile properties however, Charpy V-notch specimens tested in the L-T orientation showed impact energy values four times higher than those in the T-L orientation. When fatigue tested, microstructural banding in the steel caused secondary cracking normal to the primary crack direction which in turn was found to influence crack propagation and fracture resistance. Discontinuous bands normal to the direction of the primary fracture plane (L-T orientation) were beneficial in resisting crack extension whereas, when the bands were continuous (T-L orientation), they were detrimental to the overall fracture process. The morphology of secondary cracking in the L-T orientation was different to the secondary cracking observed in the T-L orientation. Secondary cracking in the L-T orientation promoted crack arrest and resulted in higher mechanical properties when compared with specimens tested in T-L orientation.

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Fracture Studies on High Hardness BISALLOY 500[®] Steel

Executive Summary

This study was undertaken to address to problems associated with cracking in the Australian Army's ASLAV 25 vehicles which are constructed using a high hardness armour steel. In the study, a steel similar to the armour steel was investigated and key properties were determined indicating tensile strength, fracture toughness, impact resistance, resistance to stress corrosion cracking and cyclic fatigue cracking. The characteristics chosen for investigation are those which provide an understanding of cracking problems, performance limits of the steel and assist in the development of a through-life support program which was requested by the Army for this type of armour.

The strength and fracture toughness properties obtained were typical of this type of high hardness steel. In addition, this study identified that the armour steel was highly susceptible to stress corrosion cracking in an environment of natural seawater and it is therefore emphasised that appropriate protection of vehicle from such an environment must be provided to prevent the occurrence of extensive cracking. The study also found that slow cracking under fatigue loading was influenced by the microstructure in certain orientations relative to the rolling direction of the steel.

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Dr. M.Z. Shah Khan is currently a senior research scientist in Maritime Platforms Division. He has researched on the fracture and fatigue behavior of metallic materials in support of the structural integrity of Army and Naval platforms. His current interests are in the study of fracture, fatigue and behaviour under dynamic loading rates of naval composite materials.



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1. Introduction

The Australian Army is currently deploying Light armoured vehicles (LAV's) to enhance troop mobility. To increase vehicle mobility and troop performance, vehicle manufacturers have turned to high hardness armour steel in reduced thickness to achieve a light-weight vehicle without compromising ballistic protection. In earlier batches of high hardness armour steel used in the fabrication of LAV 25 armoured vehicles, widespread cracking was reported either during or after fabrication [1]. This cracking has been generally designated as delayed cracking, the precise mechanism of which is unknown. Because of this, considerable uncertainty has been created in the steel's long term structural integrity.

An earlier study showed that fatigue crack growth rates were sensitive to the type of load spectrum applied and that microstructural banding in the steel influenced the crack growth mechanism [2]. Banding is a common feature of hot rolled low alloy steels [3-6], and the theories regarding their formation are well postulated [7-9]. Microstructural banding, depending on its orientation with respect to the rolling direction, has also been shown to effect other mechanical properties including the fracture behaviour of steels [10-12].

The purpose of the present work was to characterise a high hardness steel, similar to the one used in LAV 25 vehicles, in terms of its tensile properties, fracture toughness, impact resistance, resistance to stress corrosion cracking and cyclic fatigue cracking. The range of characteristics chosen for investigation are those which provide a framework in designing structural materials for military application. In addition, these properties are important as they provide performance limits of the steel which could be used as a ready reference in defect tolerance, structural integrity and through-life structural support of the Australian Army ASLAV 25 vehicles. An attempt was also made to correlate the material properties and fracture behaviour with the banding orientation in the armour steel.

2. Experimental Procedure

2.1 Material

The test material used was BISALLOY 500® steel having a hardness in the range of 477-534 HB. Table 1 shows the as-supplied chemical composition of the steel plate, while Figure 1 illustrates optically the microstructure of the steel. An interesting feature in the steel's microstructure was banding which is due to segregation of microalloying elements during the hot rolling process.

Table 1: Chemical Composition of BISALLOY 500® steel as supplied by the vendor

Chemical Composition	C	P	Mn	Si	S	Ni	Cr	Mo	Al	Ti	B-sol*
Ladle analysis, max. wt. %	0.32	0.025	0.70	0.30	0.008	0.35	1.20	0.25	0.07	0.03	0.002

* Amount of Boron in solid solution

In all tests, two specimen orientations were studied, one designated as L-T and the other T-L. The first and second letters in each designation indicate to the direction normal to the crack plane and the expected crack propagation direction respectively.

2.2 Tensile Tests

Tensile tests were conducted on a Riehle screw driven universal testing machine at a crosshead speed of approximately 0.01 mm/sec. Tensile specimens with a rectangular cross section were machine cut to a test gauge length of 50 mm, Figure 1. Specimens were machined with the gauge length parallel to the L-T and T-L orientations with respect to the plate rolling direction. The results reported for each orientation were the average of two tests.

2.3 Charpy Impact Tests

Tests were conducted on full size Charpy V-notch specimens at a temperature of 22°C. The specimen notch was aligned to the L-T and T-L orientations with respect to the plate rolling direction, Figure 1. Three specimens for each orientation were tested in a pendulum Charpy impact tester.

2.4 Fracture Toughness Tests

Fracture toughness tests were conducted using a servo-hydraulic test machine under load control. Compact tension type specimens were tested under quasi-static loading condition within the rate range recommended in ASTM E399 standard [13]. Prior to testing, specimens with machine notch were fatigue precracked to a starting a/W ratio of approximately 0.5, see Figure 1. Load versus crosshead displacement plot were obtained from tests and an arbitrary estimate of the fracture toughness, K_{max} (MPa \sqrt{m}), was carried out using the P_{max} values in the appropriate K-solution given for a compact tension type specimen geometry [14].

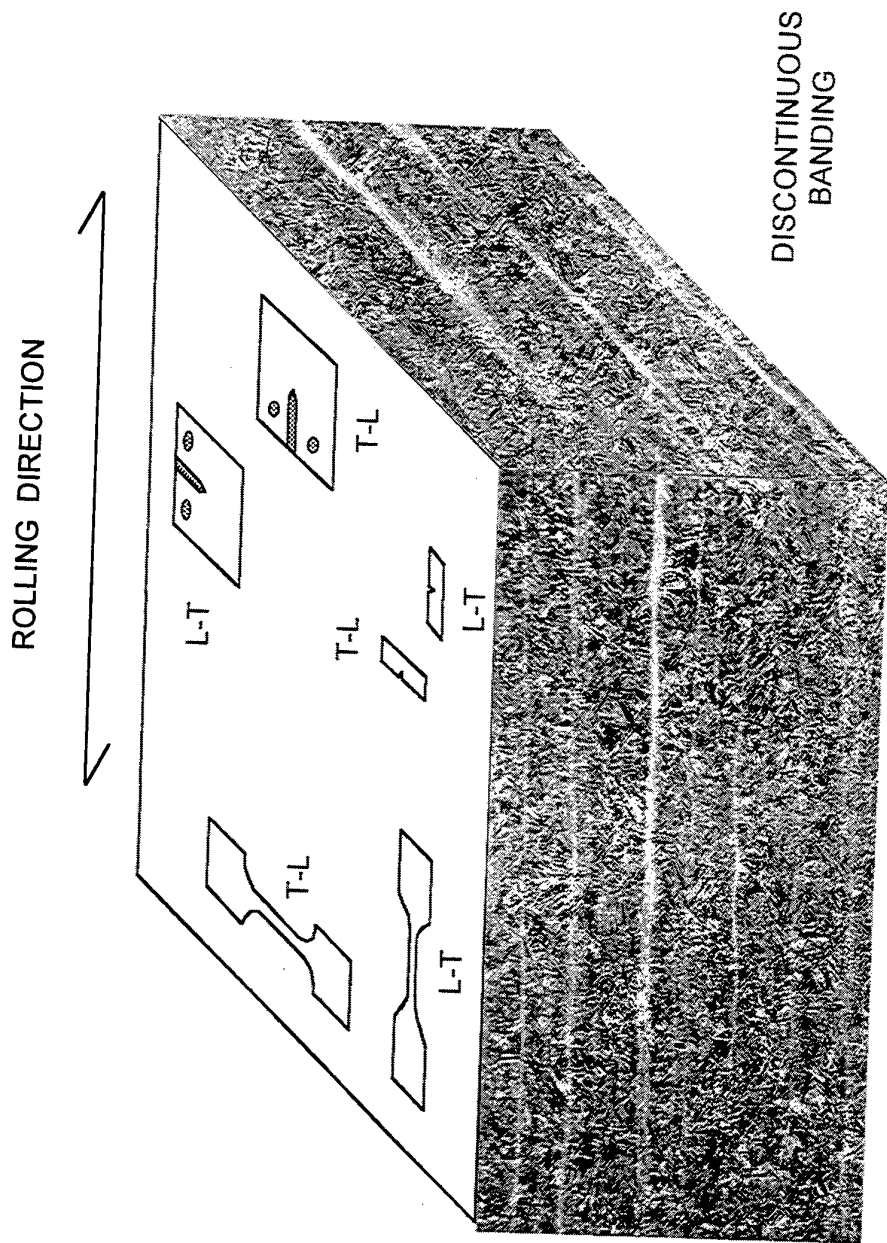


Figure 1: As-received BISALLOY 500® plate showing the optical microstructure with banding and geometry of test specimens with respect to the rolling direction

2.5 Stress Corrosion Cracking Tests

Tests were carried out in circulating seawater (free corrosion potential) and humid environment (21 °C and 80% RH). Compact tension type specimens (Figure 1) in L-T orientation were fatigue precracked to a starting a/W ratio of approximately 0.5. The applied stress intensities were calculated using the K-solution as used before in the fracture toughness tests [14][12]. Results were plotted showing the applied stress intensity versus time-to-failure.

2.6 Constant Amplitude Fatigue Tests

In these experiments, precracked compact tension specimens (same as in Figure 1) were fatigued at 5 Hz and 10 Hz using a zero-to tension sine waveform. The crack length was determined from changes in compliance measured during the tests. The applied stress intensity and crack length and were calculated using the solutions given in [14,15]. Results are presented in terms of crack growth rate, da/dN , versus stress intensity, ΔK .

2.7 Optical Metallography and Fractography

Optical metallography was carried out to reveal the microstructure and the banding in the steel with respect to the rolling direction. Examination of fracture surfaces of tested specimens was undertaken using a scanning electron microscope to ascertain the influence of banding in the fracture behaviour.

3. Results

3.1 Tensile Tests

In these tests, results show that specimen orientation had only a small effect on the 0.2% proof stress with specimens in L-T showing a marginally higher strength than those in T-L orientation. The ultimate tensile strength remained unaffected by specimen orientation whereas, elongation values in the L-T orientation were slightly higher than in T-L orientation, see Table 2.

Table 2: Tensile properties of BISALLOY 500®

Specimen Orientation	0.2% Proof Stress (MPa)	UTS (MPa)	Elongation (%)
L-T	1340	1810	13
L-T	1370	1820	12
T-L	1290	1810	11
T-L	1340	1810	11

3.2 Charpy Impact Tests

The Charpy V-notch energies obtained for the two orientations are shown in Table 3. In these tests the loading rate was much higher than the rate applied in the fracture toughness tests. Under this condition, a significantly higher fracture energy was observed for specimens with notches in L-T orientation when compared with the T-L orientation.

Table 3: Charpy V-notch energy data for BISALLOY 500®

Specimen Orientation [*]	Charpy V-notch Energy (J)
L-T [*]	41
L-T	41
L-T	41
T-L	11
T-L	12
T-L	14

^{*} Using two letter codes such as T-S or L-T for specimen orientation, the first letter in the code designates the direction of the normal to the fracture plane and the second letter denotes the direction of the expected crack propagation; T, S and L are long transverse, short transverse and rolling directions respectively.

3.3 Fracture Toughness

Results from the fracture toughness tests are shown in Table 4. Toughness in the L-T orientation was slightly greater than in T-L orientation, a result consistent with the previous trend shown with Charpy impact specimens.

Table 4: Fracture toughness of BISALLOY 500®

Notch Orientation	K _{max} (MPa.√m)
L-T	121
T-L	111

3.4 Stress corrosion cracking behaviour

The BISALLOY 500® was found to be highly susceptible to stress corrosion cracking (SCC) failure when exposed in an environment of natural seawater; SCC failure occurred in a time-to-failure (t_f) of 60 hours at an applied stress intensity (K_{appl}) as low as 27.5 MPa.√m. Figure 2, plotted in the form of K_{appl} versus (t_f), illustrates the test results obtained in natural seawater and in an environment typical of that observed in the Australian tropics. In contrast to the results obtained in natural seawater the BISALLOY 500®, when exposed to tropical environment, showed no SCC failure after 1000 hours even at a K_{appl} as high as 85.4 MPa.√m.

3.5 Fatigue behaviour

Constant amplitude fatigue tests results showed that regions of the curves depicting stable fatigue crack growth were not influenced by the fatigue frequency in both T-L and L-T notch orientations, see Figures 3, 4, 5 and 6. However, the L-T orientation had noticeable effect on crack growth rates as shown in Figures 3,4 and 5. Crack growth retardation was observed at both 5 Hz and 10 Hz test frequencies however, the onset of retardation occurred at a higher stress intensity when the fatigue test frequency was at 5 Hz (Figure 5).

3.6 Microstructure and Fractography

Figure 1 shows the optical microstructure in the as-received condition. A significant feature was the microstructural banding approximately 5 μm thick when viewed across the thickness of the plate. An electron microprobe analysis of the bands indicated segregation of elements Cr, Mo, Mn and Si, see Figure 7. The banding was observed to be continuous in the rolling direction whereas, the banding was discontinuous across the rolling direction, see Figure 1. This banding influenced significantly the cracking mechanism and the mechanical properties of the steel. SEM analysis of the fracture surfaces showed secondary cracking in a plane normal to the primary crack plane and coincided with the banding in the microstructure. For specimens with (T-L) orientation the secondary cracks were continuous and aligned with the banding, Figure 8a. The secondary cracks were discontinuous in specimens with (L-T) orientation and aligned with bands having similar nature of discontinuity, Figure 8b.

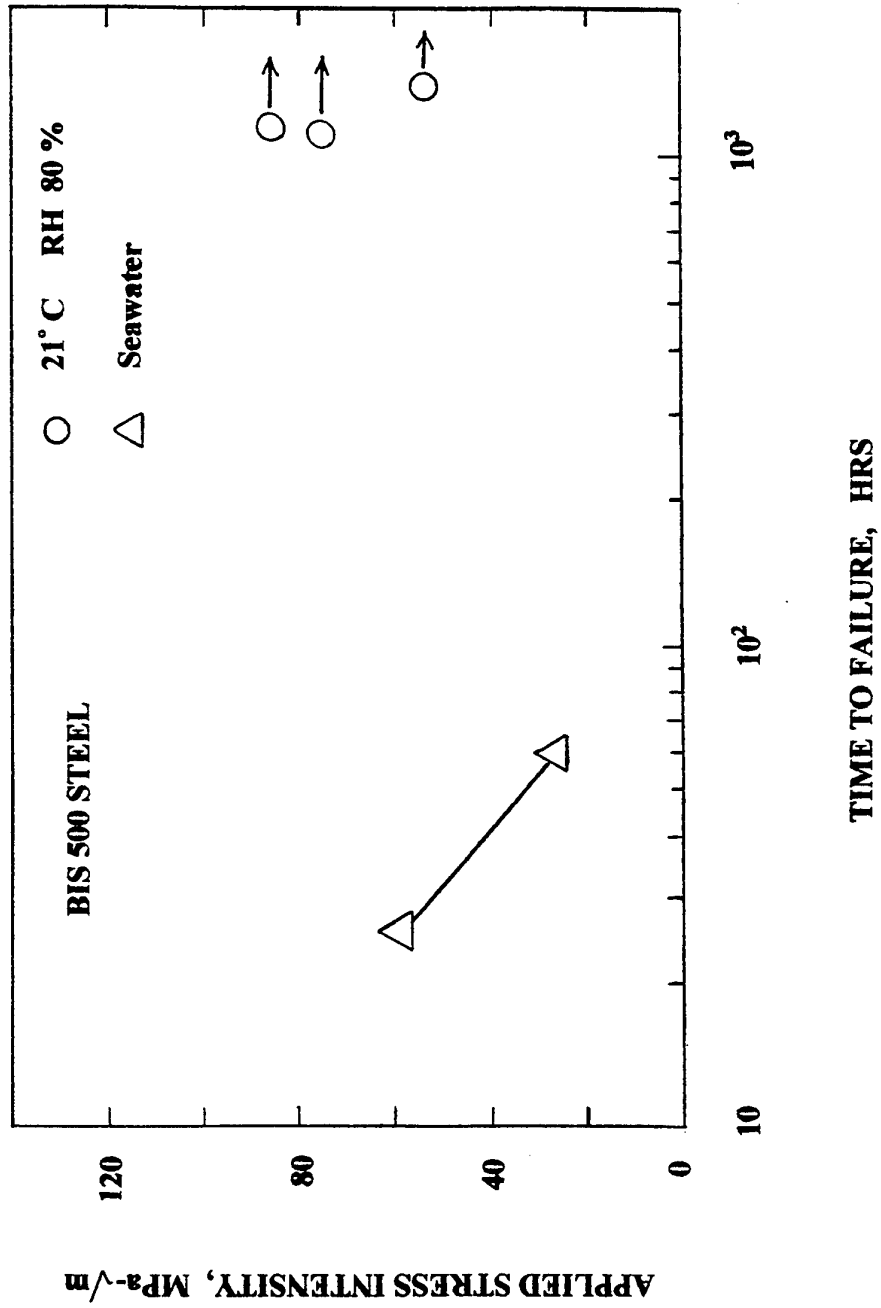


Figure 2: As-received BISALLOY 500® plate showing the optical microstructure with banding and geometry of test specimens with respect to the rolling direction

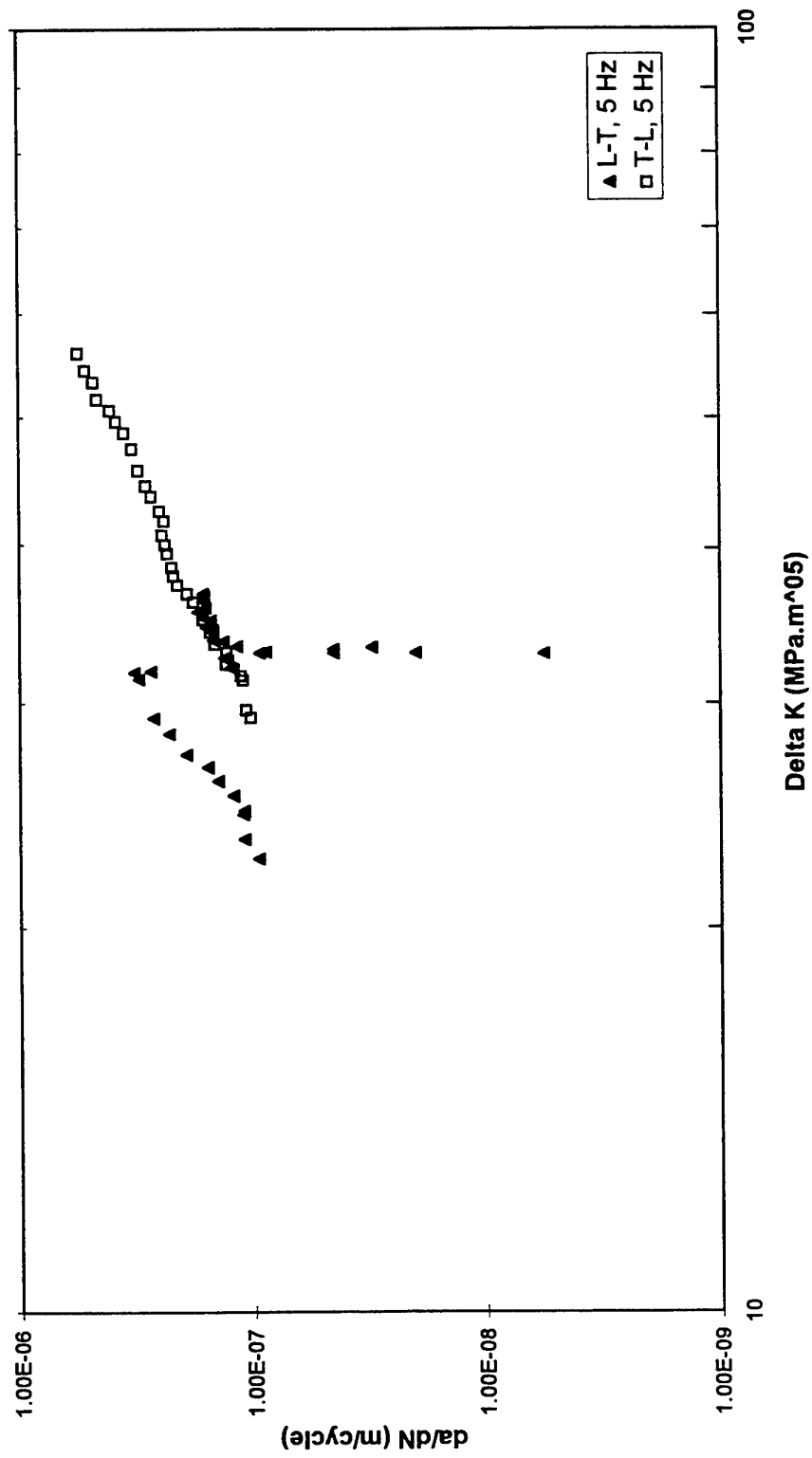


Figure 3: Effect of orientation on fatigue crack growth rates at 5 Hz

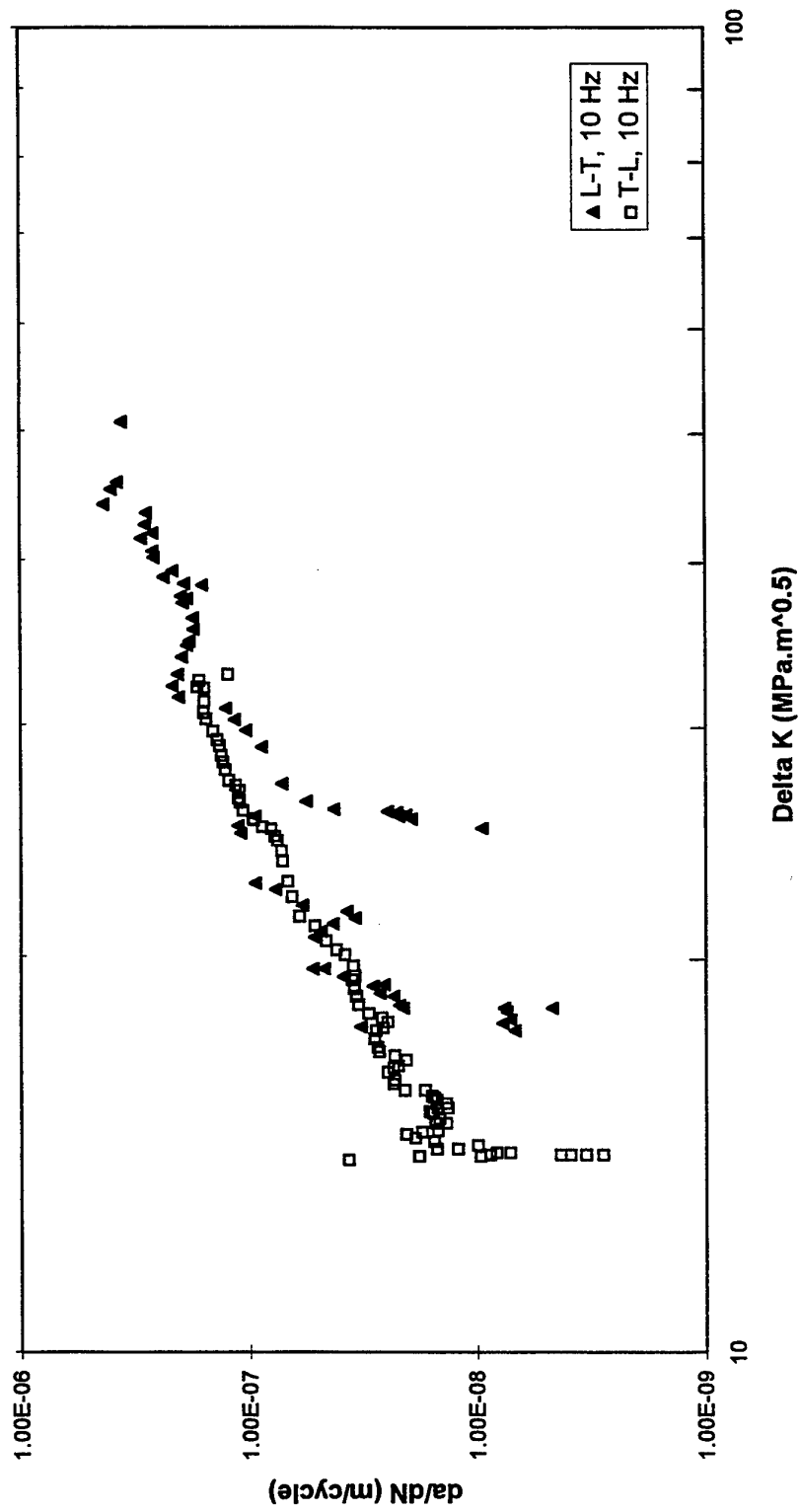


Figure 4: Effect of orientation on fatigue crack growth rates at 10 Hz

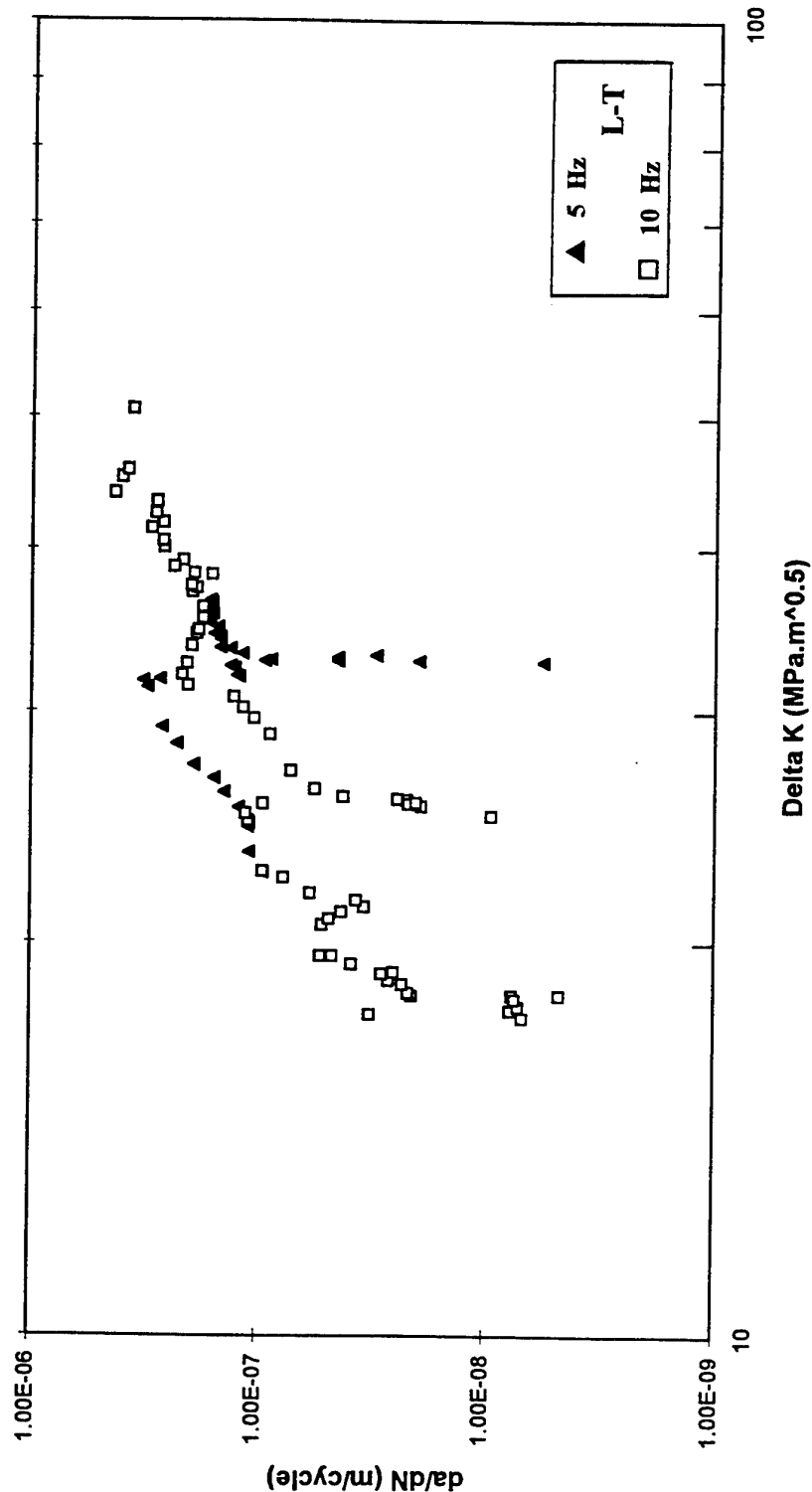


Figure 5: Effect of frequency on crack growth rates for specimens in L-T orientation

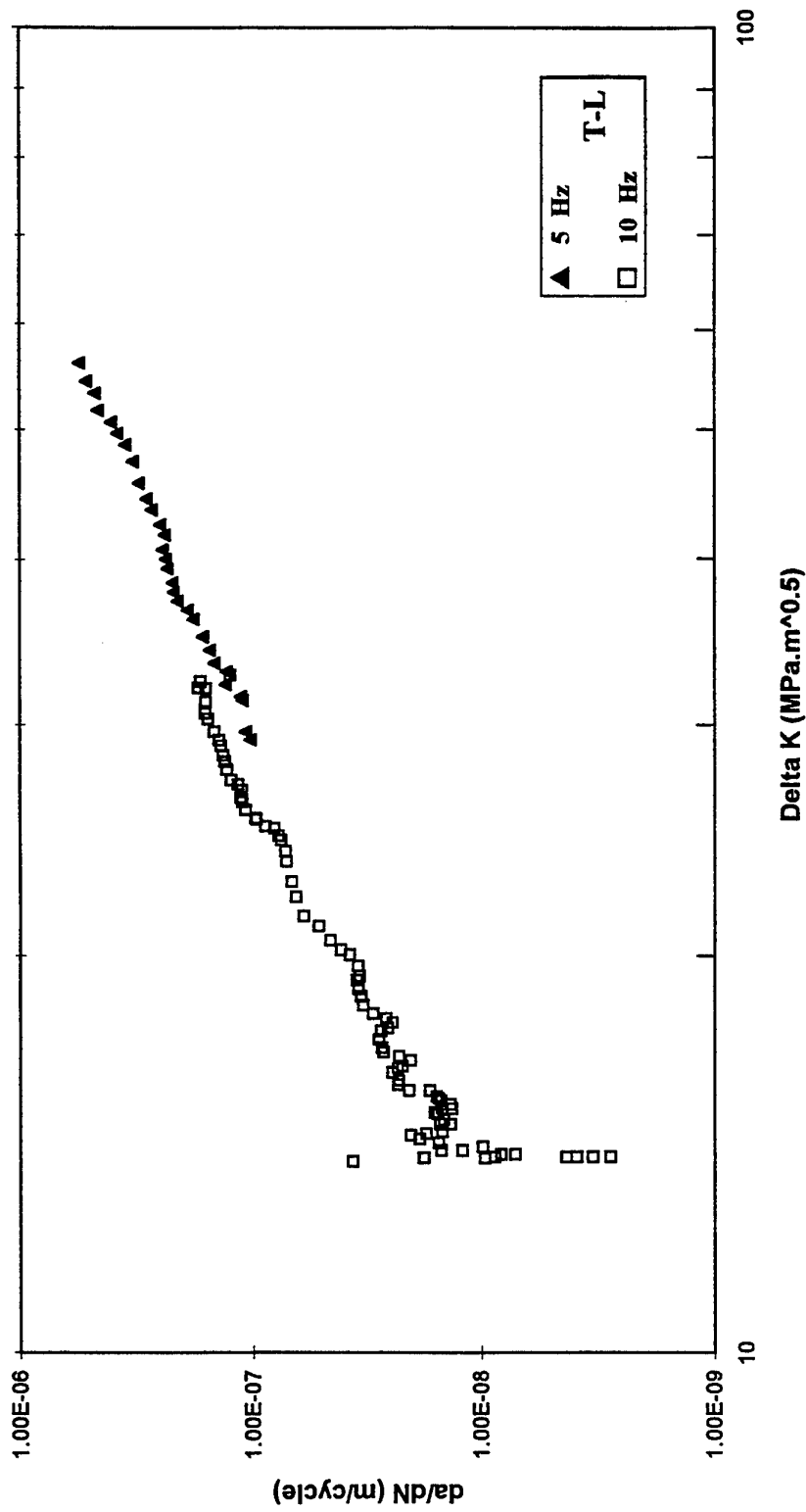


Figure 6: Effect of frequency on crack growth rates for specimens in T-L orientation

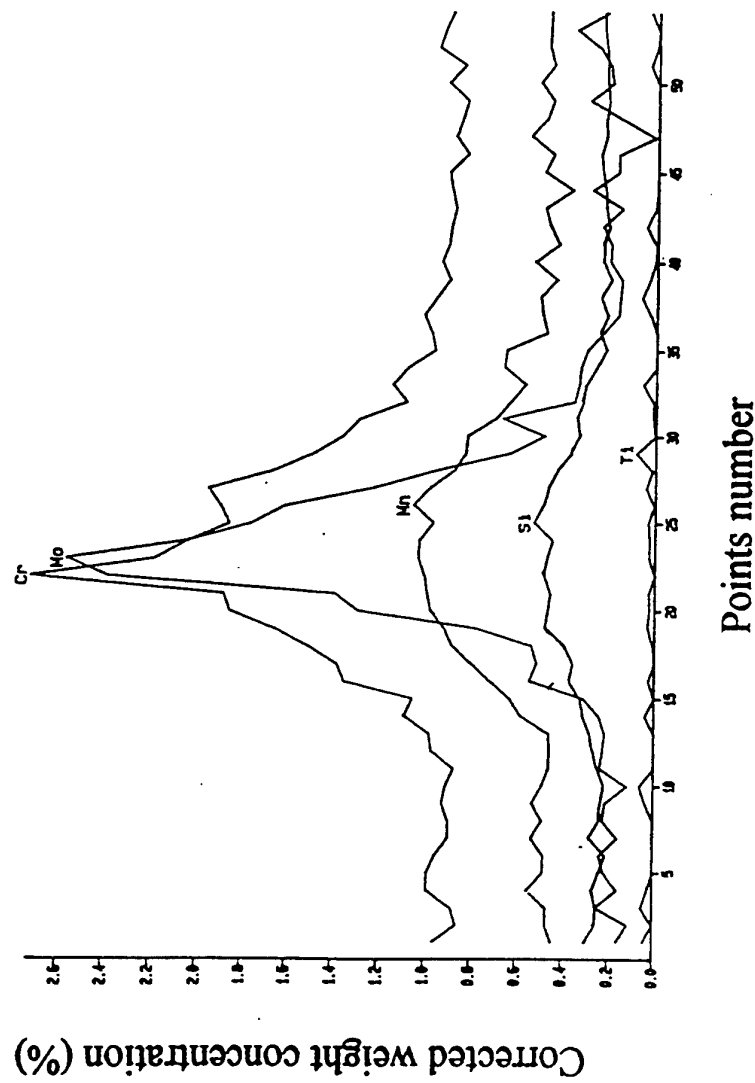


Figure 7: Electron microprobe analysis showing the concentration of alloying elements in the segregation band

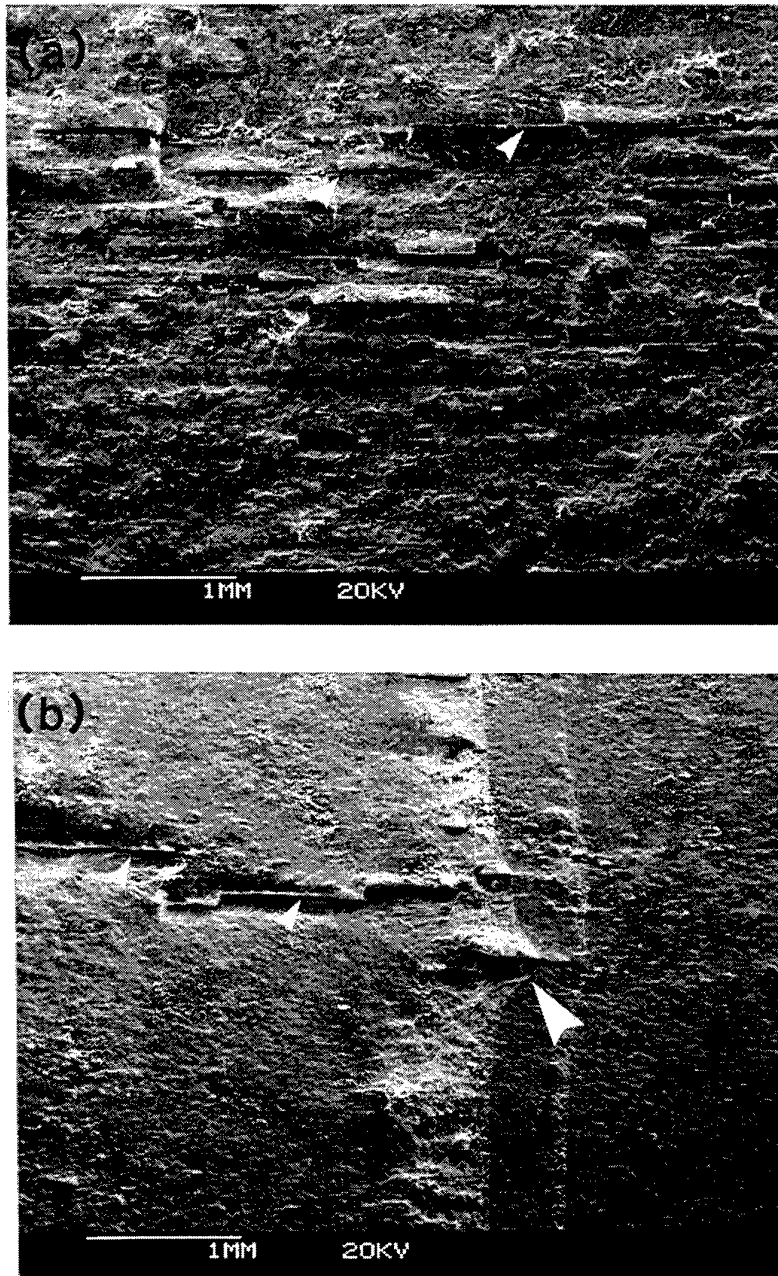


Figure 8: SEM views of the fatigue fracture surfaces in (a) T-L and (b) L-T notch orientations. Small arrows indicate morphology of secondary cracking and large arrow indicates crack growth retardation. The primary crack growth direction is from right to left.

4. Discussion

Microstructural banding has been known to influence the mechanical properties, fracture toughness and fracture behaviour of steels and the degree of their influence depend on the orientation of the test specimens relative crack growth direction [10-12]. Heiser and Hertzberg [10] categorised the influence of microstructural bands on impact resistance as crack arrester or crack divider in specimens with their primary crack front normal to the direction of banding. The authors found that samples in T-S and L-T orientations yielded higher Charpy V-notch fracture energy because of delamination cracking at segregation bands which occurred normal to the primary crack growth direction. In contrast, samples tested in S-L orientation yielded lower fracture energy due to the delamination cracking at segregation bands occurring in the primary growth direction. Thaulow et al [11] found fracture toughness depended strongly on the specimen orientation with respect to the elongated sulphide inclusions in controlled rolled C-Mn steel. The authors showed that elongated sulphide inclusions caused splitting similar in appearance to the secondary cracking reported in this study. In the present work, microstructural bands in BISALLOY 500[®] steel either appeared continuous or discontinuous depending on whether the specimen is in L-T or T-L orientation, Figure 1. When viewed from the direction where the crack front is normal to the rolling direction of the plate (L-T), the bands appear discontinuous. The bands however appear continuous when viewed from the direction (T-L) where the crack front is parallel to the rolling direction. Because of these differences in the orientation of the bands and their influence on the cracking behaviour, properties such as tensile strength, Charpy impact resistance, fracture toughness and fatigue resistance were inferior in the T-L orientation when compared with the same properties in L-T orientation.

The examination of fracture surfaces showed two distinct morphologies of secondary cracking in the primary fracture plane. For specimens in (T-L) the secondary cracking observed coincided with the continuous layers of microstructural bands in the steel and appeared shallow giving a flat appearance to the primary fracture plane. For the specimen in the L-T orientation the secondary cracking which coincided with the discontinuous microstructural bands was deeper in the plane normal to the direction of the primary fracture plane and was considered the major factor in promoting crack arrest.

In assessing a steel for military application, the role of secondary cracking should be taken into account. Although this study has shown that secondary cracking in specimens with L-T orientation was a beneficial factor in resisting slow fracture and fatigue crack progression, its presence may be detrimental to other critical properties such as shock and ballistic impact fracture resistance.

5. Conclusions

The tensile mechanical properties, fracture toughness, fatigue and stress corrosion cracking behaviour of the BISALLOY 500® steel have been found to be influenced by banding in the microstructure. The presence of banding promotes secondary cracking at the leading edge of the primary crack which results in differences in the fracture morphology and fatigue crack rates. The secondary cracking which coincided with the direction of the continuous microstructural bands (T-L) resulted in a flat fracture appearance and an overall decrease in mechanical properties. In contrast, when the primary crack front passed through discontinuous banding as was the case for specimens in the L-T orientation, the fracture surface showed the initiation of secondary cracks normal to the fracture plane and caused the arrest of the primary crack front resulting in the improvement of fatigue crack growth resistance. In addition, Charpy impact and tensile properties were also higher in the L-T orientation.

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